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Deformation and mechanical behavior of the drill pipe during subsea production tree installation

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ABSTRACT

The article presents an analytical model to study the deformation and mechanical behavior of the drill pipe during subsea production tree (SPT) installation. Lateral and axial loads were considered, including the ocean wave, ocean current, drill pipe size, and SPT weight that might dominate the deformation and mechanical behavior of the pipe. And the finite difference method and Gauss-Jordan elimination method were used to solve the established nonlinear analysis model. The results indicate that the ocean current, water depth, and drill pipe size are the main factors affecting the lateral displacement of the last node of drill pipe and mechanical behavior of the pipe at lift-off point and thus need to be considered when designing such installation process.

Keywords: Subsea production tree installation; Deformation; Mechanical behavior; Drill pipe; Finite difference method.

INTRODUCTION

Due to the fact that installation process of subsea production tree (SPT) directly affects the success of ocean oil production, more attention needs to be paid during SPT installation. Nowadays, the method of SPT installation using drill pipe is among the most widely used methods in petroleum industry due to its high effectiveness and economic efficiency. Serious risks to the operators' lives and economic losses might be caused when a destructive accident happens to the installation equipment under extreme ocean environment. In order to assure the safety of SPT installation structures duration its installation process, the deformation and mechanical behaviors of the pipe need to be carefully evaluated.The literatures offer many research studies on the installation of the SPT. Gardner and Kotch (1976) introduced an efficient and accurate solution of the responses of pipe during SPT installation by establishing the computational model. Safai (1983) analyzed the variation of pipe bending stress using ABAQUS software when the pipe is subjected to the wave loads. Park et al (2002; 2003) conducted several research studies on dynamic numerical analysis of the marine risers and low-tension cables based on the FEM method. Xu and Wang (2012) introduced a linear iteration scheme to solve the nonlinear equations. Gong (2013) established an analysis model of the pipe with boundary conditions at different installation stages and examined the model using the finite element method. The researches mentioned above were obtained by the FEM method whose effectiveness has been accepted by the engineering community. Nevertheless, each application case needs to be carried out and the nonlinear calculations with local defective element will be inefficient by using this method. The theoretical analysis therefore is necessary. Raman-Nair and Baddour (2003) established a mathematical model to analyze the response of the pipe during SPT installation by using Kane's formalism, where the pipe is modelled using lumped masses connected by extensional and rotational springs, including structural damping. Wu et al. (2014) applied the Newmark-β method and Newton-Raphson iteration method to obtain the numerical solution for the hand-off drill pipe. Bai et al. (2014) performed mechanical research on a manifold installation by drill pipe in deep water that considered the wave loads and lowering velocity. This theoretical method was proved to be accurate using numerical simulation based on OrcaFlex software. Fei et al. (2020) evaluated the effects of surging and heaving movements of installation platform on mechanical behaviors of the pipe and investigated the operability envelopes for SPT installation. However, researches in the previous focused only on the response characteristics of the slender structure at a constant depth during SPT installation, and the effects of ocean environment and SPT weight were neglected.

The aim of the research reported here was to propose a mathematical model to investigate the deformation and mechanical behavior of the drill pipe during SPT installation to decrease the risks of SPT installation and structural failure problems. An analysis model of the installation pipe was established considering all the loads that loaded on the pipe, and finite difference method was used to solute the proposed mathematical model. Results obtained by OrcaFlex simulation were used to verify the validation of the proposed mathematical model. The ocean environment including ocean wave, current, and water depth and pipe specification and SPT weight that might affect the deforestation and strength performance of the pipe were evaluated based on the proposed model.

ANALYSIS MODEL

As shown in Figure 1, the SPT and drill pipe are together lowered from the float platform positioned at sea surface to the subsea wellhead at seabed after the conductor is installed. During installing the SPT, the drill pipe is subjected to the axial tension force generated by the float platform, weight of drill pipe and SPT, and lateral force generated by ocean wave and current. The global coordinate system (x, z) is used with its origin at the lift-off point of the float platform in this article. The x axis is set parallel to the horizontal plane, and the positive direction is same as that of lateral force. And the z axis is vertically set pointing to the mudline underwater.

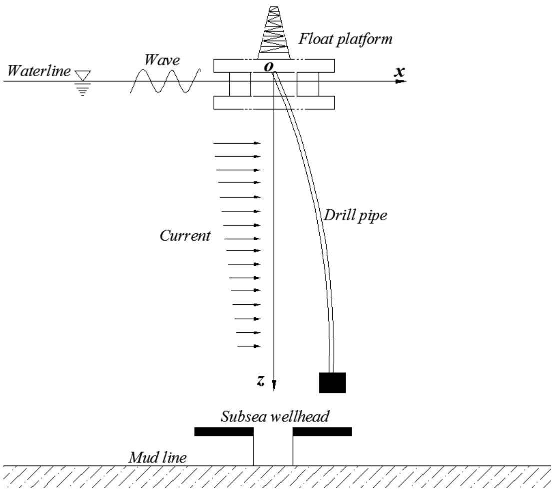


Figure 1. Schematic diagram of SPT installation using drill pipe.

2.1 Governing Equation

Considering the equilibrium of the vertical force V, horizontal force H, and the bending moment M of a differential drill pipe with length ds, as shown in Figure 2, the equilibrium equations for the drill pipe segment can be set as follows:

$$\begin{cases} dH + q\sin\theta ds = 0 \\ dV - p\cos\theta ds = 0 \\ dM - H\sin\theta ds + V\cos\theta ds = 0 \end{cases} \tag{1}$$

where θ is the inclination slop of the pipe, ds is the length of the differential pipe segment, p is the vertical force generated by submerged weight of the pipe and SPT, and q is the lateral force generated by ocean wave and current. The geometric relationship of these parameters can be obtained as $cos\theta=dx$, $sin\theta=dz$, $dx/ds=1/(1+(dz/dx))^{-0.5}$. And the bending moment of the drill pipe can be obtained by multiplying the bending stiffness EI and the curvature as $M=EId\theta/ds$.

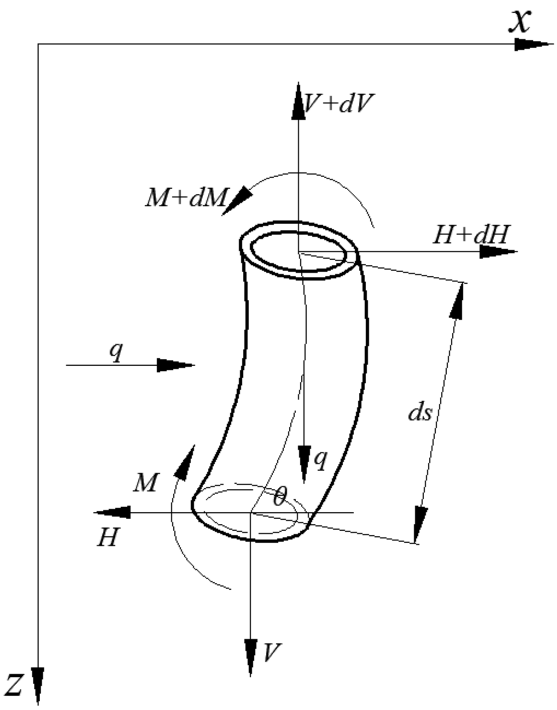


Figure 2. Sketch of a differential drill pipe.

Then, the governing equation can be obtained as follows:

$$\frac{d^2}{dz^2}\left[EI(z)\frac{d^2x}{dz^2}\right] - p(z)\frac{d^2x}{dz^2} = q(z) \tag{2}$$

Due to the vertical force loaded on the pipe vary with water depth, wave height, wave period, and current velocity, the analytical solution of the governing equation mentioned above can hardly be obtained directly. By using the finite differential method, the drill pipe can be divided into *n+1* number of segments starting from the lift-off point of the float platform which denoted the first node (No. *0*) to the pipe end connecting with SPT which denoted the last node (No. *n+1*). Considering the derivatives with difference quotient term, the governing equation of Eq. (2) can be obtained as

$$\frac{EI}{h^4}\cdot x_{i+2}-\left[\frac{4EI}{h^4}+\frac{p(z_i)}{h^2}\right]\cdot x_{i+1}+\left[\frac{6EI}{h^4}+\frac{2p(z_i)}{h^2}\right]\cdot x_i-\left[\frac{4EI}{h^4}+\frac{p(z_i)}{h^2}\right]\cdot x_{i-1}+\frac{EI}{h^4}\cdot x_{i-2}=q(z_i) \tag{3}$$

where h is the length of each segment of the drill pipe and x_i and z_i are the coordinates of the No. (*i*) Node on the x axis and z axis, respectively. The SPT is suspended by the drill pipe at the last node during the SPT installation, and the vertical force $p(z_i)$ generated by each node submerged weight of the pipe and SPT can be obtained as follows:

$$p(z_i)=P_{SPT}+0.25\pi(\rho_s-\rho_w)(D_o^2-D_i^2)(L-z_i) \tag{4}$$

where P_{SPT} is submerged weight of the SPT, ρ_s is the density of the drill pipe, ρ_w is the density of sea water, D_o is outer diameter of the pipe, D_i is inner diameter of the pipe, and L is the depth of ocean. The lateral force generated by ocean wave and current can be obtained according to the Morison equation as (Gosse and Barsdale, 1969)

$$q(z_i)=0.5C_D\rho_w D_o(u_w+u_c)|u_w+u_c|+0.25\pi C_M\rho_w D_o^2 a_w \tag{5}$$

where C_D is the drag force coefficient, C_M is the inertia force coefficient, u_{wi} is the horizontal velocity of ocean wave particle at z_i depth, u_{ci} is the ocean current velocity at z_i depth, and a_{wi} is the horizontal acceleration of ocean wave particle. According to the airy wave theory, the horizontal velocity and acceleration of ocean wave particle can be obtained as (Ortega, Rivera and Larsen, 2018)

$$u_w(z_i)=\frac{\pi H_w}{T_w}\exp(-k\cdot z_i)\cdot\cos(kx-\omega_w t) \tag{6}$$

$$a_w(z_i)=\frac{2\pi^2 H_w}{T_w^2}\exp(-k\cdot z_i)\cdot\sin(kx-\omega_w t) \tag{7}$$

where Hw is the wave height, Tw is the wave period, k is the wave number, and ωw is the wave circular frequency. And ocean current velocity can be obtained according to the Ekman transport theory (Michael and Joseph, 2013) as

$$u_c(z_i)=V_s\left(\frac{L-z_i}{L}\right)^{1/7} \tag{8}$$

where V_s is the tidal velocity.

2.2 Boundary Conditions

The lift-off point at the top end of drill pipe is fixed to the float platform, and the SPT is attached to the bottom end of the drill pipe during its installation process. Because the lateral force loaded on the SPT is far less than that of the drill pipe, the SPT to be installed is considered as a mass point distributed on the lower end of the pipe. Then, the deformation and slope angle of the drill pipe at the lift-off point and the bending moment of the drill pipe at the bottom end are equal to zero. Therefore, the boundary conditions of the drill pipe can be obtained as follows:

$$\begin{aligned} & x\big|_{z_i=0} = 0 \\ & \theta\big|_{z_i=0} = \frac{dx}{dz}\bigg|_{z_i=0} = 0 \\ & M\big|_{z_i=L} = EI\frac{d^2x}{dz^2}\bigg|_{z_i=L} = 0 \\ & Q\big|_{z_i=L} = \left(EI\frac{d^3x}{dz^3} - p(z_i)\frac{dx}{dz}\right)\bigg|_{z_i=L} = q(z_L) \end{aligned} \tag{9}$$

where $q(z_L)$ is the lateral force acting on the SPT and the bottom end of the pipe and Q and M are the shearing force and bending moment acting on the drill pipe, respectively.

2.3 Model Solution

In order to assure the continuation at the first node (No. *0*) and the last node (No. $n+1$) by using the finite difference method, the drill pipe needs to be extended upward and downward, respectively, as shown in Figure 3. Then, ($n+5$) nodes in total can be obtained including the fictitious extended nodes of No.-*1*, No.-*2*, No. n+1, and No. $n+2$. Then, there are ($n+5$) unknown parameters of the of the whole drill pipe during SPT installation ($x_{-2}, x_{-1}, x_0, x_1, x_{n+1}, x_{n+2}$). Moreover, ($n+1$) equations can be deduced according to the governing equation in Eq. (3):

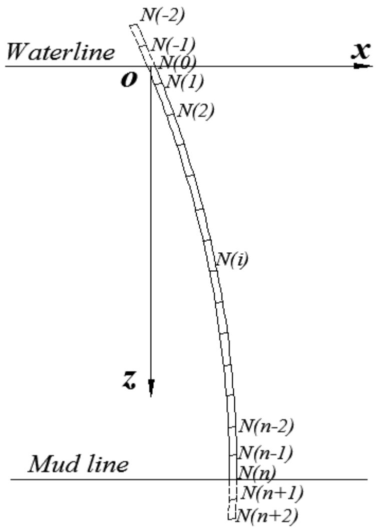


Figure 3. Schematic diagram of drill pipe discretization.

Additionally, four other equations can be obtained according to the boundary conditions of Eq. (9), which can be expressed as follows:

$$
\begin{aligned}
&x_0 = 0 \\
&x_1 - x_0 = 0 \\
&x_{n+1} - 2x_n + x_{n-1} = 0 \\
&\left[EI - h^2 p(z_L)\right]x_{n+1} - \left[3EI - h^2 p(z_L)\right]x_n + 3EIx_{n-1} - EIx_{n-2} = h^3 q(z_L)
\end{aligned}
\tag{10}
$$

Then, the ($n+5$) unknown parameters can be solved according to the ($n+5$) obtained equations, and matrix form of these equations can be expressed as

$$[M]\cdot[X]=[q] \tag{11}$$

where $[M]$ is the coefficient matrix, $[X]= [x_{-2}\ x_{-1}\ x_0\ x_1 ...\ x_{n+1}\ x_{n+2}]^T$ is the unknown matrix of deformation of the drill pipe at each discrete node, and $[q]= [\ q_0\ q_1\ q_2 ...\ q_n\ 0\ 0\ 0\ h^2q(z_L)]^T$ is the matrix of known parameters. For the governing equation and boundary equations from Eq. (3) to Eq. (10) which form the coefficient matrix belonging to large sparse matrix, the Gauss–Jordan elimination method could be used to solve the deformation of the discrete node of the drill pipe. An augmented matrix could be established according to the coefficient matrix $[M]$ and $[q]$ formed by the lateral force acting on each node of the pipe as follows:

$$|A| = \begin{vmatrix} m_{11} & m_{12} & \cdots & m_{1n} & q_1 \\ m_{21} & m_{22} & \cdots & m_{2n} & q_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} & q_n \end{vmatrix} \tag{12}$$

Then, establish an array $pos[n]$ and initialize the array which is used to preserve the pivot element of each row of the established augmented matrix:

$$|A| = \begin{vmatrix} m_{11} & m_{12} & \cdots & m_{1n} & q_1 \\ m_{21} & m_{22} & \cdots & m_{2n} & q_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} & q_n \end{vmatrix} \tag{13}$$

Then, the deformation of each discrete node of the drill pipe $[X]$ could be obtained using the Gauss–Jordan elimination method (Stanimirović and Petković, 2013).

CASE STUDY AND DISCUSSION

3.1 Case Study

To illustrate the previous model with examples, an actual case of SPT installation is selected with its basic parameters including the density of pipe $\rho_s=7850\ kg.m^{-3}$, density of seawater $\rho_w =1030kg.m^{-3}$, and Young's modulus of the pipe $E=210GPa$. The values of the drag force coefficient C_D and the inertia force coefficient C_M were taken as 1.2 and 1.0, respectively, as suggested by Techet (2004). And a comparison between the proposed model and OrcaFlex simulation has been established with submerged weight $P_{SPT} =300kN$, water depth $L=1000m$, tidal velocity

$V_s=1.0m/s$, wave height $H_w=6m$, wave period $T_w=8s$, and $5in$ drill pipe (the outer diameter of the pipe $D_o=127mm$ and inner diameter of the pipe $D_i=101.6mm$).

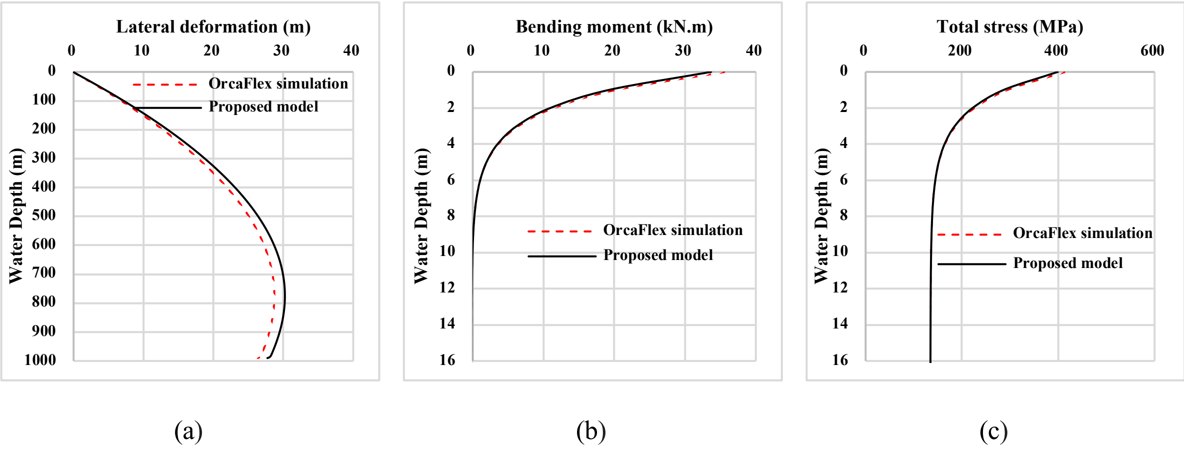


Figure 4. Comparisons of the proposed model and OrcaFlex simulation: (a) lateral deformation of drill pipe, (b) bending moment of drill pipe, and (c) total stress of drill pipe.

In order to verify the accuracy of the mathematical model established in this article, a comparison of the latera deformation, bending moment, and total stress of pipe, simulated by OrcaFlex and calculated by the proposed model, was made. Both the simulation model and mathematical model had the same structures and encountered the same environment loads. As shown in Figure 4, the deformation and mechanical behaviors of the pipe given in this article coincided well with the results obtained using OrcaFlex simulation, and the errors between them are <5%. Therefore, the accurate deformation and mechanical behaviors of the SPT installation pipe can be obtained by the mathematical model proposed in this article.

As shown in Figure 4, the lateral deformation of the pipe increased obviously at shallow water and varied slowly at deep water. The largest lateral deformation of the pipe appears near the bottom end of the pipe. The bending moment and total stress of the pipe decrease dramatically with water depth and remain unchanged while the pipe is below 10m, which is contrary to the variation of the largest value of the lateral deformation of the pipe, the maximum bending moment, and total stress of the pipe located at the lift-off point of the pipe. However, all the variations of deformation, bending moment, and total stress of the pipe with installation depth show a trend of dramatic incensement at shallow water and increase slowly at deep water.

3.2 Effects of Ocean Environment

3.2.1 Effect of Ocean Wave

To evaluate the effects of ocean wave on the deformation and mechanical behaviors of the pipe during SPT installation, different ocean height (which ranges from 4m to 8m) and ocean period (which ranges from 6s to 10s) are applied on the drill pipe.

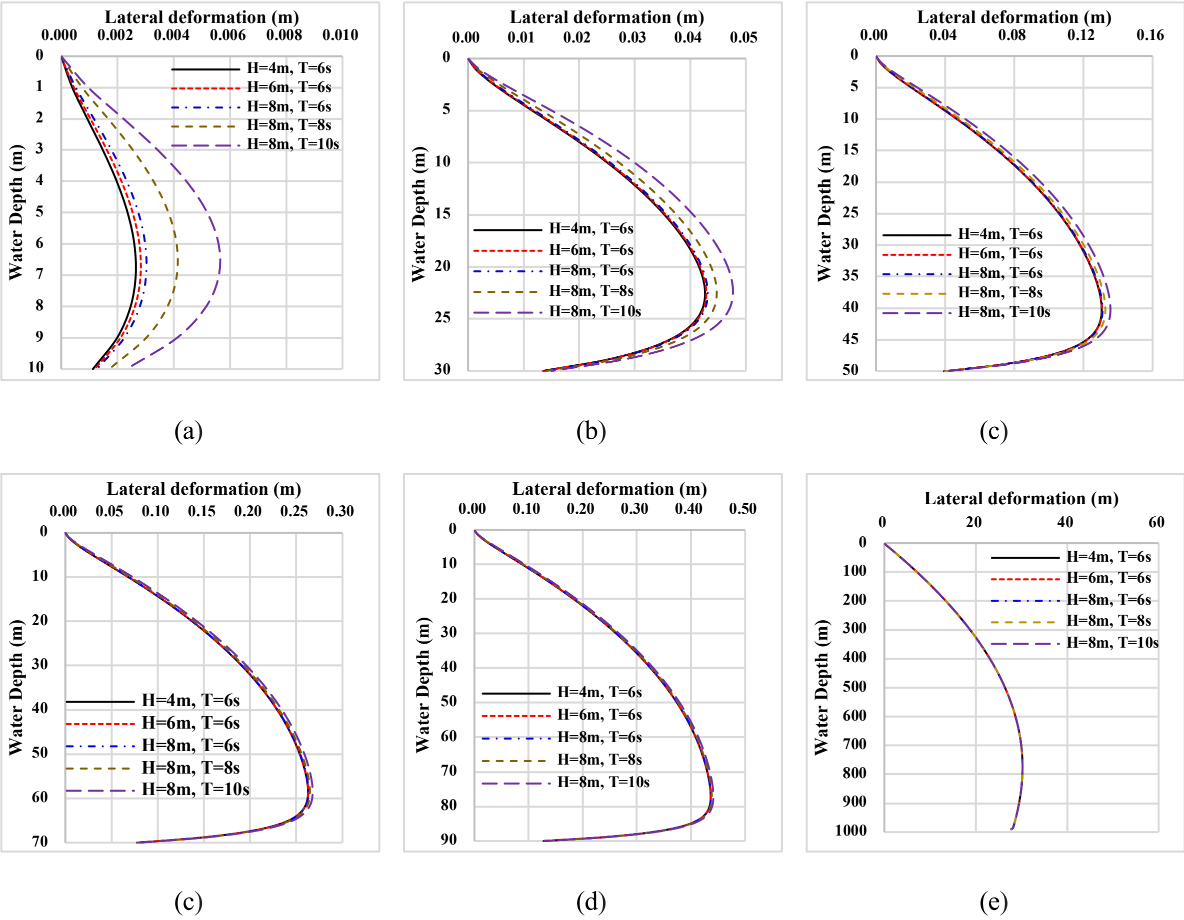
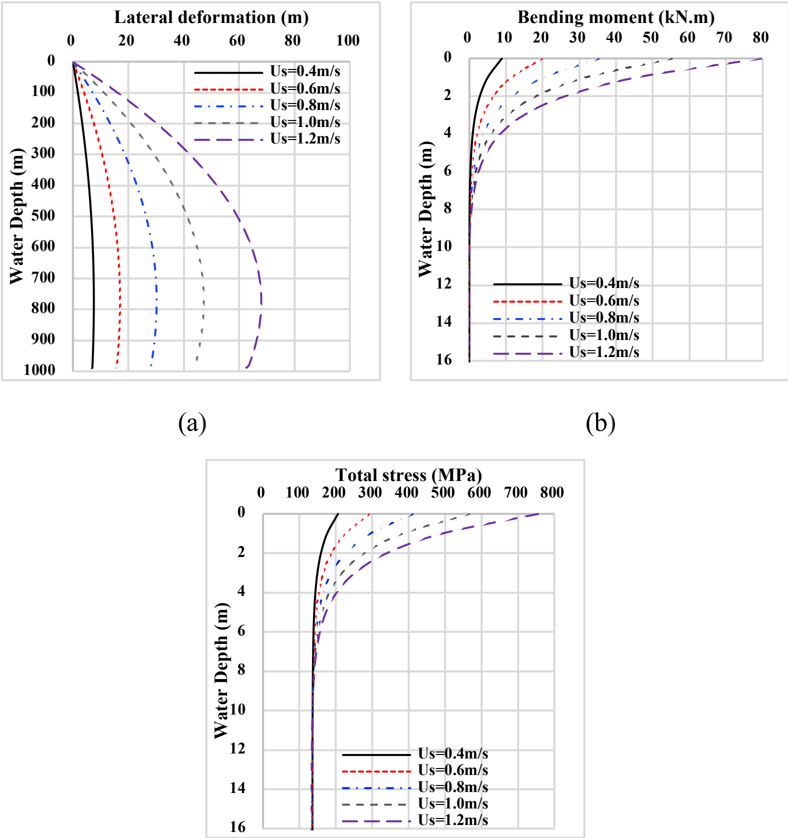


Figure 5. Lateral deformations of the pipe under different ocean waves with water depth of (a) 10m, (b) 30m, (c) 50m, (d) 70m, (e) 90m, and (f) 1000m.

As shown in Figure 5, the ocean wave affects the deformation of the pipe a lot when the SPT is lowered at shallow water. Compared with lateral deformation of the pipe under different ocean heights, the lateral deformation varies significantly with the ocean period. However, the lateral deformation of the pipe is almost the same under different ocean height and ocean period when the SPT is lowered at deep water, as shown in Figure 5(e) and Figure 5(f). In ocean engineering, the SPT needs to be installed mostly underwater to gather oil and gas in deep water area. Then, the effect of the ocean wave applied on the drill pipe can be ignored during analyzing deformation and mechanical behavior of pipe in the SPT installation process.

3.2.2 Effect of Current

The ocean wave is one of important factors that affect the deformation and mechanical properties of the drill pipe during the SPT installation. The effects of ocean current on the lateral deformation, bending moment, and total stress of the drill pipe predicted by the proposed model derived in this article are depicted in Figure 6. The tidal velocity was considered as varying from 0.4m/s to 1.2m/s, which covers most ocean environments. And the parameters used are assumed to be same as in Section 3.1 in this case.



(a) (b)

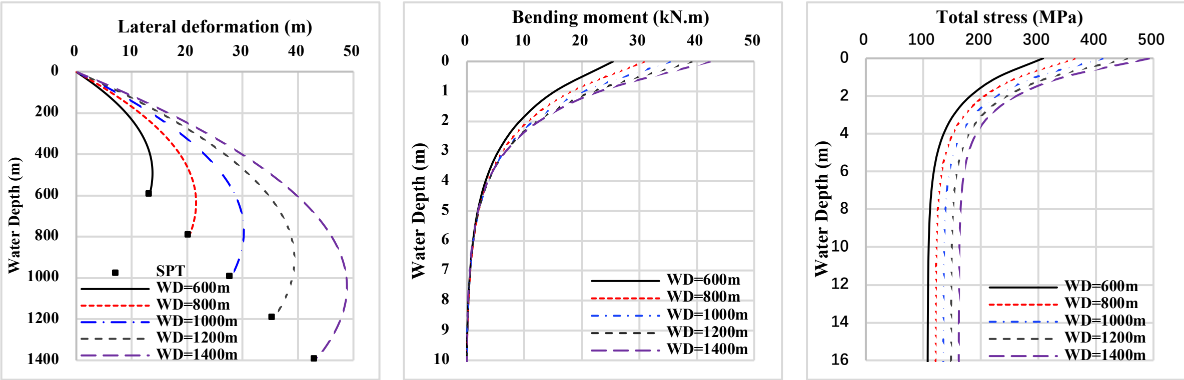
(c)

Figure 6. Effect of ocean wave on the pipe during SPT installation: (a) lateral deformation of drill pipe, (b) bending moment of drill pipe, and (c) total stress of drill pipe.

As shown in Figure 6, the lateral deformation, bending moment, and total stress of the pipe, contrary to the effect of ocean wave on the drill pipe, increase significantly with the tidal velocity. The last node of the pipe, which adjusted the SPT at bottom end, is away from subsea wellhead *62.4m*. And the maximum total stress which appears at the lift-off point is *757.6MPa* which approaches the yield strength of the drill pipe. Therefore, the lateral deformation and total stress of the pipe need to be accurately evaluated before SPT is lowered in each SPT installation process to prevent excessive bending deformation of the drill pipe.

3.2.3 Effect of Water Depth

As the SPT needs to be lowered underwater with different depths gradually, five depth points varying from *600m* to *1400m* were selected to evaluate the deformation and mechanical behavior of the drill pipe. As shown in Figure 7, the variation of the deformation, bending moment, and total stress of the pipe under different water depth predicted by the proposed model are obtained. The lateral deformation of the pipe increases gradually with the installation depth of the SPT, and the displacement of SPT away from subsea wellhead is roughly in a linear relationship with the water depth, as shown in Figure 7 (a). And the drill pipe has higher bending moment and total stress when the SPT is lowered in deeper water.

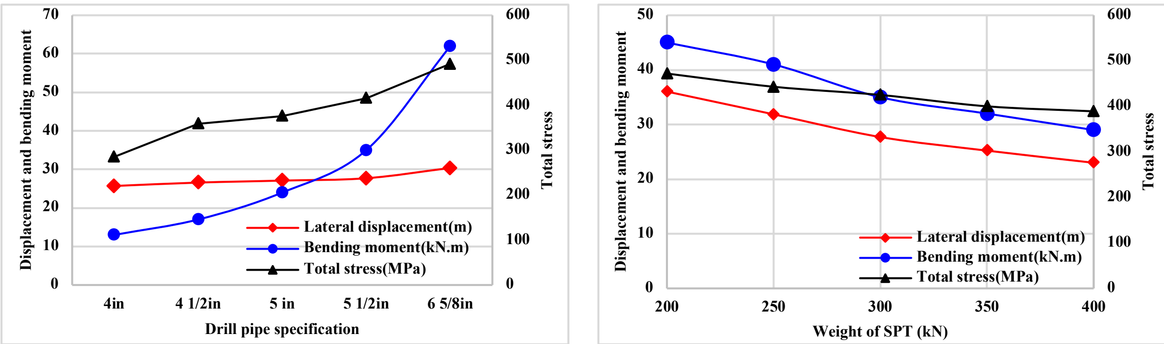


(a) (b) (c)

Figure 7. Variation of deformation and mechanical behaviour of pipe with water depth: (a) lateral deformation of drill pipe, (b) bending moment of drill pipe, and (c) total stress of drill pipe.

3.3 Effect of Drill Pipe Size and SPT weight

The drill pipe size and weight of SPT affect the deformation and mechanical behavior of the pipe during the SPT installation. The maximum displacement of the last node of the pipe that attached the SPT, the maximum bending moment, and total stress that appear at the lift-off point are predicted according to the proposed model also, as shown in Figure 8. Five specifications of drill pipe (ranging from *4in* to *6 5/8in*) used in ocean oil and gas exploration are selected. And weight of SPT is assumed to range from *200kN* to *400kN,* covering most of the SPT.



(a) (b)

Figure 8. Maximum displacement last node, bending moment, and total stress of drill pipe under (a) different drill pipe specifications and (b) weight of SPT.

As shown in Figure 8(a), contrary to the variation of the maximum lateral displacement of the pipe that barely change with drill pipe specification, the maximum bending moment and total stress of the pipe significantly increase with drill pipe size. As a result of the mechanical behavior of the pipe mainly caused by the lateral wave, current loads, weight of SPT, and drill pipe itself, smaller size of the drill pipe should be selected to assure the safety of SPT installation process. Because the axial load caused by the SPT weight would reduce the bending moment of the pipe when the drill pipe encounters same ocean conditions, the maximum lateral displacement, bending moment, and total stress of the pipe decrease slowly with SPT weight, shown in Figure 8(b).

CONCLUSION

The deformation and mechanical behavior of the drill pipe during subsea production tree installation were investigated in this research. Different types of the axial load and lateral load were considered, including the ocean wave, ocean current, drill pipe size, and SPT weight that might dominate the deformation and mechanical behavior of the pipe during SPT installation. And the finite difference method and Gauss-Jordan elimination method were used to solve the established nonlinear partial differential equation. Based on the work done in this research, the following results and conclusions were obtained.

(a) The accuracy of the analysis model employed in this research was verified. The lateral deformation, bending moment, and total stress of the drill pipe obtained from the analysis model were in good agreement with those obtained from OrcaFlex simulation.

(b) The ocean wave applied on the drill pipe rarely affects the deformation and mechanical behavior of the pipe in deep-water area, where the SPT is mostly installed.

(c) The lateral displacement of the last node of the pipe (location of SPT adjusting the subsea wellhead) and mechanical behavior of the pipe at lift-off point (location of the maximum bending moment and total stress appears) vary with ocean wave and water depth gradually.

(d) The maximum deformation, bending moment, and total stress increase significantly with the drill pipe size and decrease slowly with SPT weight.

Based on the analysis in this paper, in order to decrease the high deformation and stress of the drill pipe during SPT installation, it would be much better to select a smaller size of drill pipe during SPT installation and evaluate the deformation and mechanical behavior of pipe under different ocean wave and water depth in detail before SPT installation.

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